CHAPTER 2

SPEED CONTROL OF 3-PHASE I.M.

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2.1 Speed Control of 3-Phase Induction Motors:

Speed control means speed variation under open loop (feed forward) or close loop conditions. We will discuss here only the principles and steady-state characteristics of speed control methods.

Induction motors are of two types - Squirrel-cage motor and Wound-rotor motor. There are various types of speed control methods of induction motor. These are:
(*i*) Pole Changing,
(*ii*) Stator Voltage Control,
(*iii*) Supply Frequency Control,
(*iv*) Star Delta Connection,
(*v*) Rotor Resistance Control,
(*vi*) *Slip Power Recovery*,

Where; (*i*) is applicable for squirrel-cage motor,
(*ii*) to (*iv*) is applicable for both wound-rotor and squirrel-cage motor and (*v*) and (*vi*) are applicable for wound-rotor.

2.1.1Speed control of squirrel-cage induction motor

2.1.1.1 Pole Changing:

For a given frequency speed is inversely proportional to number of poles. Synchronous speed, and therefore, motor speed can be changed by changing the number of poles. Provision for changing of number of poles has to be incorporated at the manufacturing stage and such a machine is called"pole changing motor" or "multi-speed motor" .In squirrel cage motor the number of poles are same as the Stator winding. So there is no provision for changing the number of poles. But for wound rotor arrangement for changing the number of poles in rotor is required, which complicates the machine. So it is only used for Squirrel cage induction motor.
A simple but expensive arrangement for changing number of stator poles is to use two separate winding which are wound for two different pole numbers. An economical and common alternative is to use single stator winding divided into few coil groups. Changing the connections of these coil groups change number of poles. Theoretically by dividing winding into a number

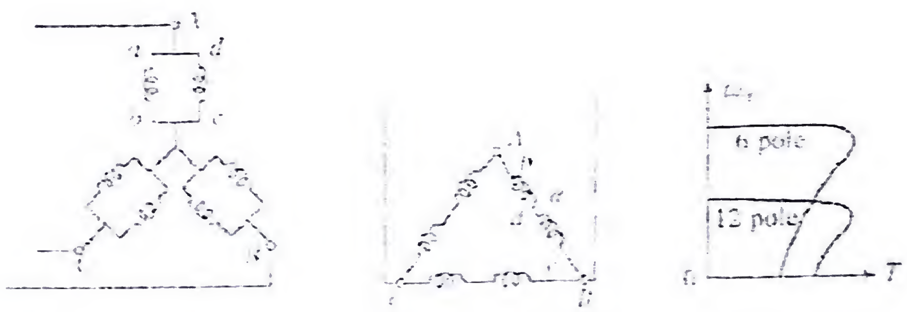
of coil group and bringing out terminals of these group a number of arrangements of different pole numbers is obtained.

Fig (2-1) Stator phase connection for 6-poles

Figure (2-1-a) above shows a phase winding consisting of six coils divided into two groups – a-b consisting of odd number coils (1, 3,5) connected in series and c-d consisting even numbered coils (2,4,6)connected in series. The coils can be made to carry currents in the given directions by connecting coil groups either in series or parallel as shown in figure B and C. With this connection machine has six poles. If the current through the coil group a-b is reversed [Fig. 3(a)], then all coils will produce north poles. Fluxes coming out of the north poles will now find paths through Interpol spaces for going out consequently producing south poles at Interpol spaces. The machine will now have 12 poles. Here again the direction of current through coils can be obtained by connecting two sections a-b and c-d either in series or parallel for both pole numbers 6 and 12.

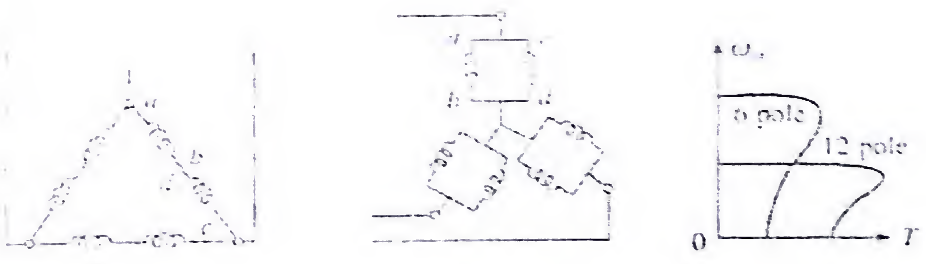
Fig (2-2) Stator phase connection for 12-pole

Further three phases of the machine can be connected to form delta or star connection by choosing a suitable combination of series and parallel connection between coil groups of each phase, and star and delta connection in each phase, speed change can be obtained with constant power or variable torque operation connections and speed-torque curves for these operations are shown in figures ((4), (5), (6))



(a) High speed (6-pole) (b) Low speed (12-pole) (c) Speed-torque curves

Figure (2-3) constant torque control



(a) High speed (6 pole) (b) Low speed (12-pole) (c) Speed-torque curves

Figure (2-4) constant power control

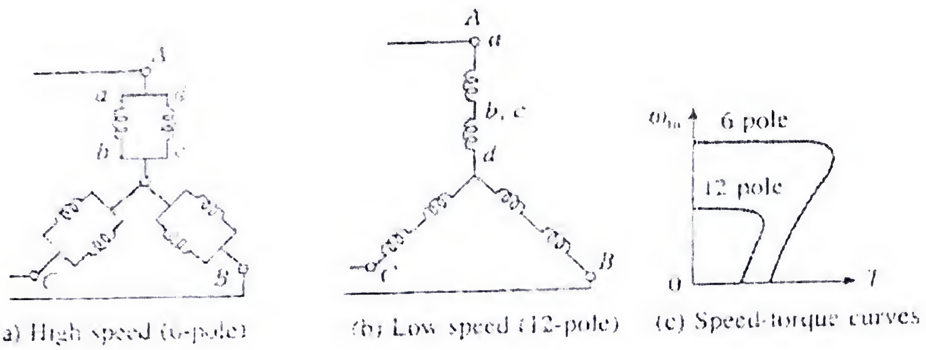


Figure (2-5) variable torque control

2.1.1.2 Stator Voltage Control:

This is a slip control method with constant frequency variable voltage being supplied to the motor stator. Obviously the voltage should only be reduced below the rated value. For a motor operating at full load slip, if the slip is to be doubled for constant load torque then the voltage must be reduced by a factor of (0.707) and the corresponding current rises to(1.414) of the full load value. The motor, therefore, tends to get overheated. The method therefore is not suitable for speed control. It has a limited use for motor driving fan type load whose torque requirement is proportional to the square of speed. It is a commonly used method for ceiling fans driven by single-phase induction motors that have large standstill impedance limiting the current drawn by the stator. Change the torque speed characteristic as shown in Fig (2-6). If the motor drive a fan load and supply voltage reduced slip will increase and motor speed will decrease as shown in figure (2-6).A variable voltage can be obtained by autotransformer or solid state voltage controller as shown in figures (2-7) and (2-8) respectively.

An advantage of autotransformer over solid state controller is that it provides a sinusoidal voltage for IM, while solid state controller produce distorted wave form, when this wave resolves by Fourier series it will contain harmonics which Increase both core and copper losses so motor has to be de rated.

Since this method decrease the developed torque and provides a small change in motor speed, so it is very convenient for fan load because the torque of this load decrease as the square of speed and the volume of pumped flowed is proportional to the cube of speed so a small change in motor speed cause a large reduction in fluid flow.

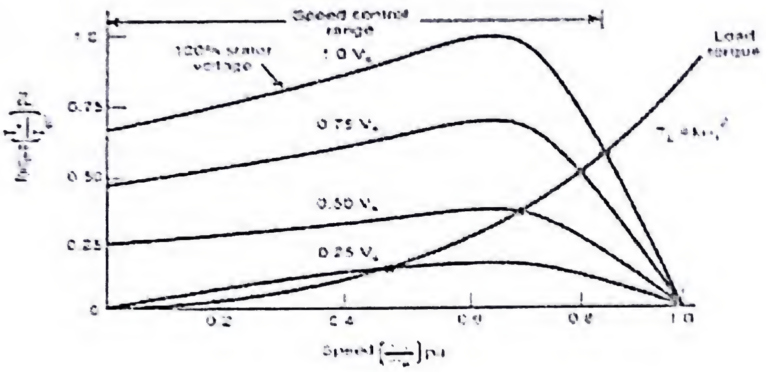


Fig (2-6) Torque speed characteristics for various value of supply voltage.

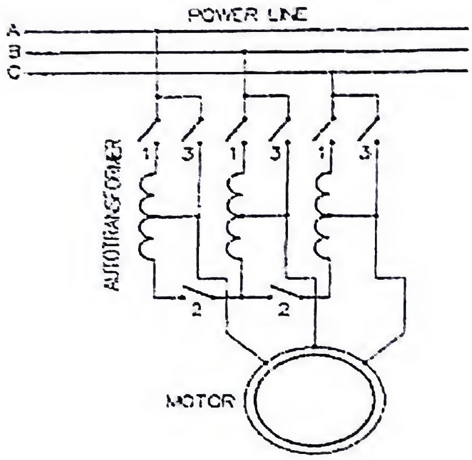


Fig (2-7) Auto transformer voltage controller

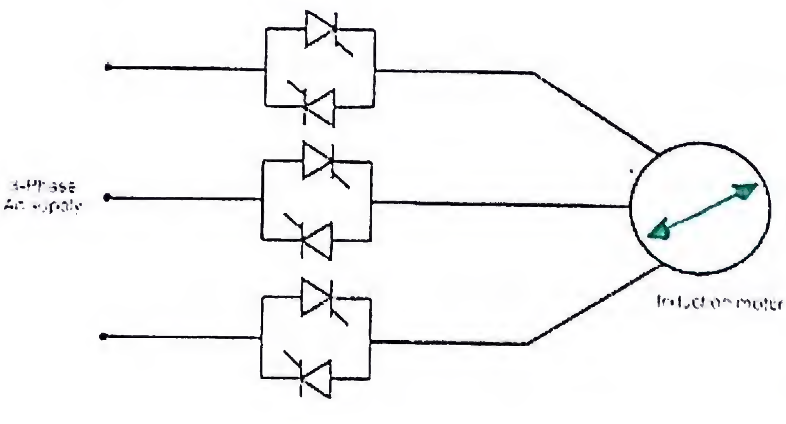


Fig (2-8) Solid static voltage controller

2.1.1.3 Supply Frequency Control:

Synchronous speed $N_s = 120(f/P)$.
And, motor speed, $N_r = (1-S)N_s$.

Now, it is evident that varying synchronous speed, which can vary by varying the supply frequency, can vary the motor speed Voltage induced in stator is proportional to the product of supply frequency, f_s and air-gap flux φ_m

$$E = 4.44 k_w \varphi_m f_s T_{ps}$$

If stator drop is neglected, then E *is equal to V*. Then the supply voltage will become proportional to f_s and φ_m.

$$V = 4.44 k_w \varphi_m f_s T_{ps}$$

Any reduction in the supply frequency f_s keeping the supply voltage constant causes the increase of air-gap flux φ_m.

Induction motors designed to operate at the knee point of the magnetization characteristic to make a full use of magnetic material. Therefore, the increase in flux will saturate the motor. This will increase the magnetizing current and distort the line current and voltage, increase in core loss and stator $I^2 R$ loss and produce a high-pitch acoustic noise. Also, a decrease in flux is also avoided to retain the torque capability of motor. Therefore, variable frequency control below rated frequency is generally carried out at rated air gap flux by varying supply voltage with frequency so as to maintain $\frac{V}{f}$ ratio constant at the rated value.

Advantages of Frequency Control:

The variable frequency control provides good running and transient performance due to the following features:

(i) Speed control and breaking operation are possible from zero speed to base speed.

(ii) During transient, the operation can be carried out at the maximum torque with reduce current giving good dynamic response.

(iii) Copper losses are low and the efficiency and power factor are high.

(iv) Drop speed from no load to full load is small.

The most important advantage of variable frequency control is that it allows a variable speed drive with above mentioned good running and transient performance to be obtained from a squirrel cage induction motor.
The squirrel cage motor has a number of advantages over a DC motor. It is cheap, rugged and long lasting. Because of absence of commutator and brushes it requires practically no maintenance; it can be operated in an explosive and contaminated environment, and can be designed for higher speeds, voltages and power ratings. Though the cost of induction motor is lesser than DC motor of same power rating but still the cost of variable frequency drive are higher in general. But because of the advantages listed above the induction motor drives of variable frequency type is mostly preferable over DC motor drives. Because of the above advantages we are dealing with this type of speed control for controlling induction motor that has a large number of industrial applications as follows:
(*i*) It can be used for any type of underground and underwater installation.
(*ii*)In applications involving explosive and contaminated environment.
(*iii*)In application in tractions, steel mills, pumps, fans, blowers, compressors, spindle drivers etc.

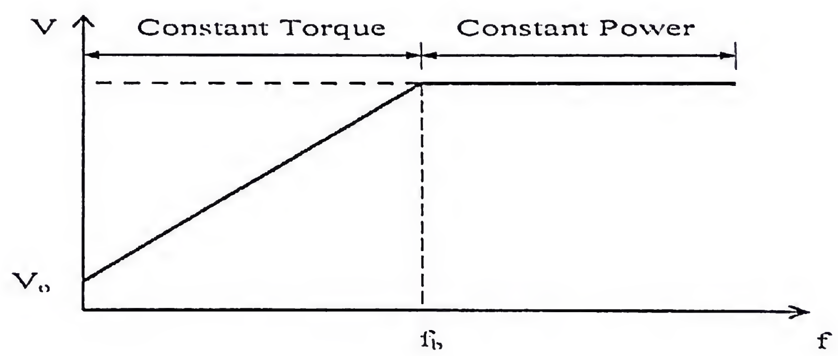
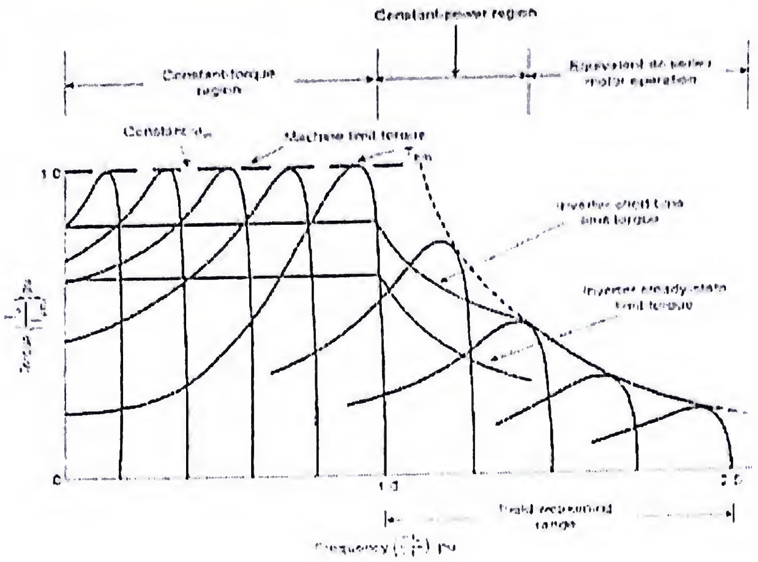


Fig (2-9) Variation in voltage with change in frequency



2.1.1.4 STAR DELTA START UP PRINCIPLES

Important that the pause between star contactor switch off and Delta contactor switch is on correct. This is because Star contactor must be reliably quenched before Delta contactor is activated. It is also important that the switch over pause is not too long.

For 415v Star Connection voltage is effectively reduced to 58% or 240v. The equivalent of 33% that is obtained with Direct Online (DOL) starting.

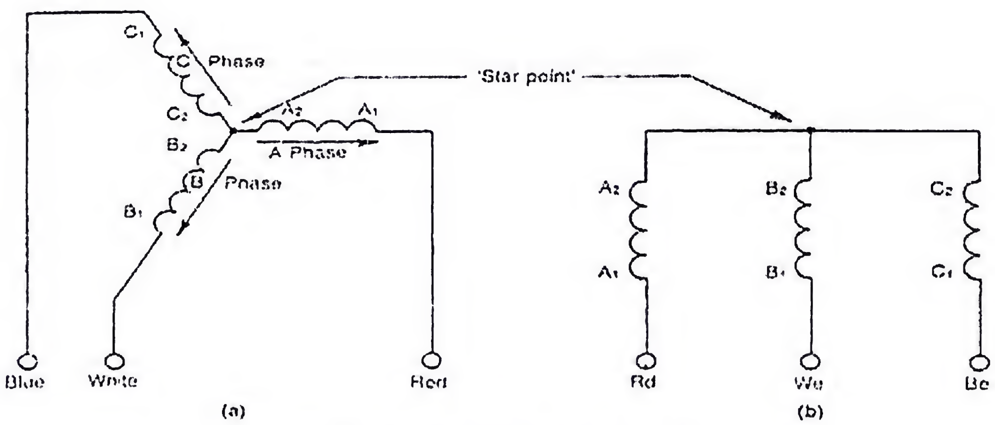


Fig. 9.18 *Three-phase star connections*

If Star connection has sufficient torque to run up to 75% or %80 of full load speed, then the motor can be connected in Delta mode.

When connected to Delta configuration the phase voltage increases by a ratio of V3 or 173%. The phase currents increase by the same ratio. The line current increases three times its value in star connection.

During transition period of switchover the motor must be free running with little deceleration. While this is happening "Coasting" it may generate a voltage of its own, and on connection to the supply this voltage can randomly add to or subtract from the applied line voltage. This is known as transient current. Only lasting a few milliseconds it causes voltage surges and spikes. Known as a changeover transient.

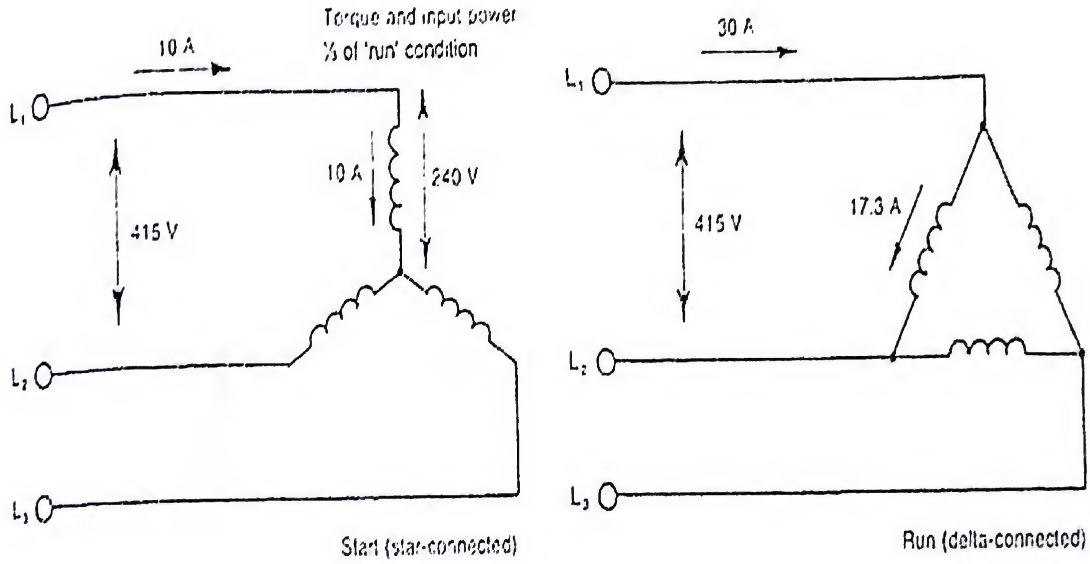
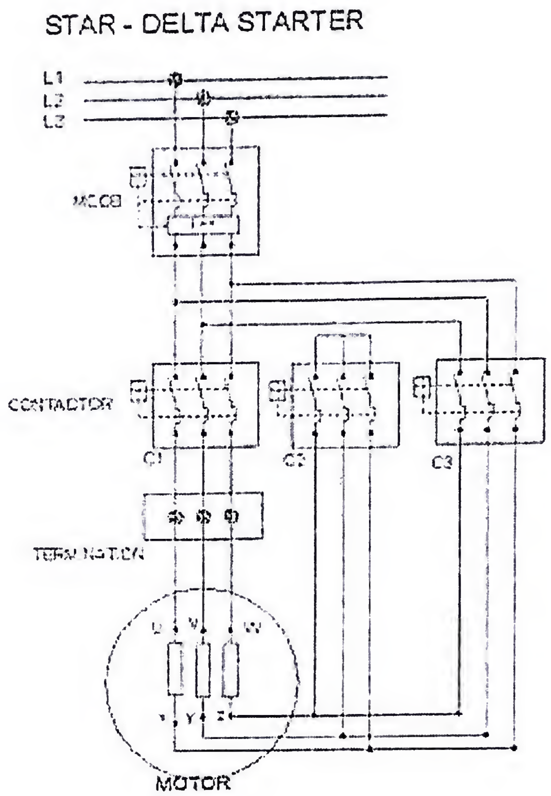
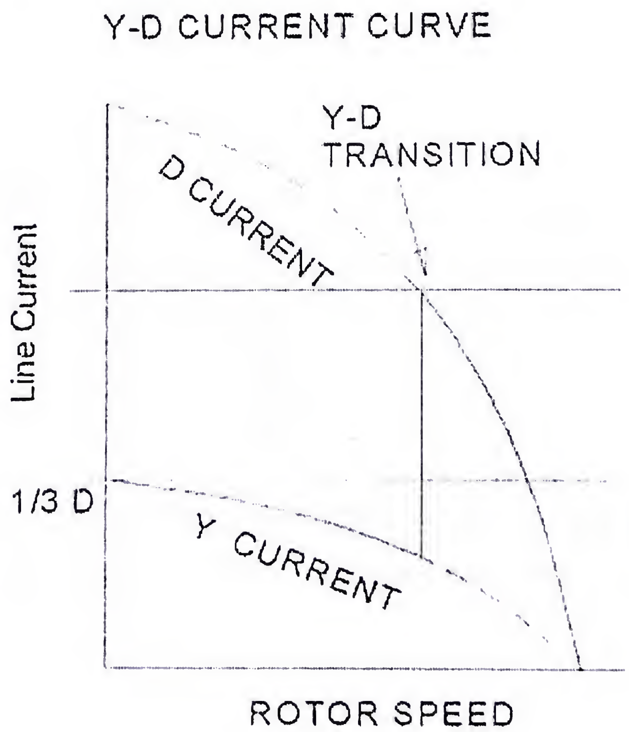
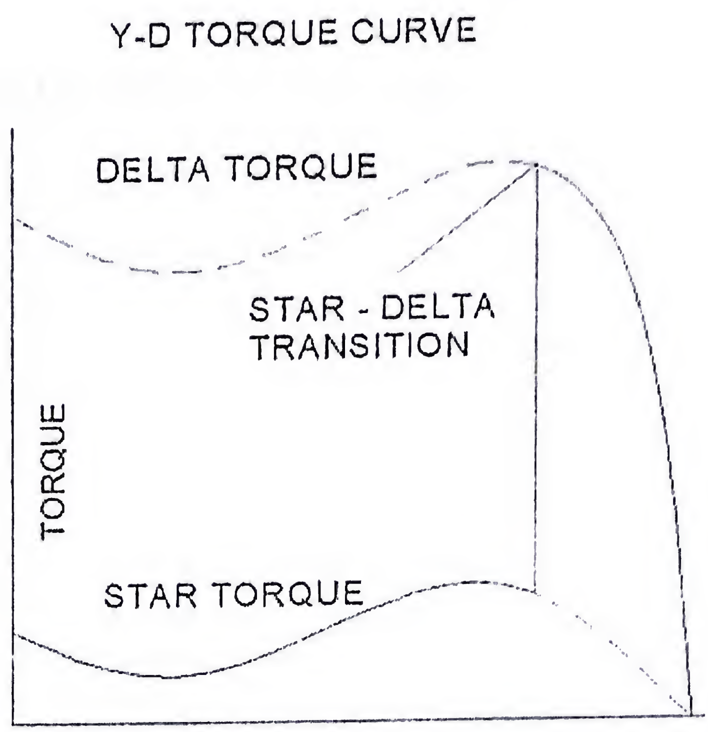


Fig. 13.1 *Comparison of star and delta starting*

Star - Delta connection







The time transition Y to D is controlled by timer, time setting is depend to motor characteristic, normally between 6 – 14 second, depend on the time consumption of motor to achieve the lowest current when Y connection

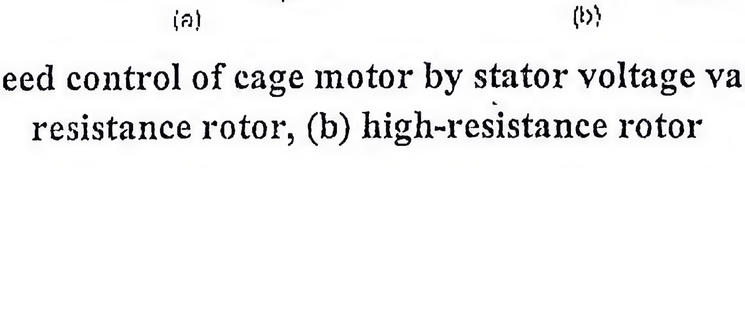


Figure (2-12) Speed control of cage motor by stator voltage variation; (a) low-resistance rotor, (b) high-resistance rotor

2.1.2 Speed control of wound rotor induction motor

A *wound rotor* induction motor has a stator like the squirrel cage induction motor, but a rotor with insulated windings brought out via slip rings and brushes. However, no power is applied to the slip rings. Their sole purpose is to allow resistance to be placed in series with the rotor windings while starting. (Figure 2-13) . This resistance is shorted out once the motor is started to make the rotor look electrically like the squirrel cage counterpart.

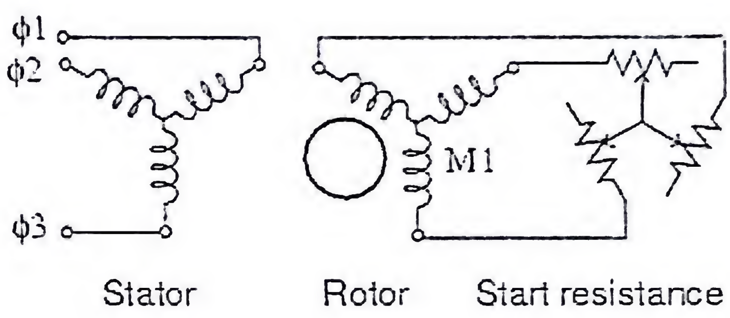


Figure (2-13) Wound rotor induction motor

Why put resistance in series with the rotor? Squirrel cage induction motors draw 500% to over 1000% of full load current (FLC) during starting. While this is not a severe problem for small motors, it is for large (10's of kW) motors. Placing resistance in series with the rotor windings not only decreases start current, locked rotor current (LRC), but also increases the starting torque, locked rotor torque (LRT). Figure below shows that by increasing the rotor resistance from R_0 to R_1 to R_2, the breakdown torque peak is shifted left to zero speed. Note that this torque peak is much higher than the starting torque available with no rotor resistance (R_0) Slip is proportional to rotor resistance, and pullout torque is proportional to slip. Thus, high torque is produced while starting.

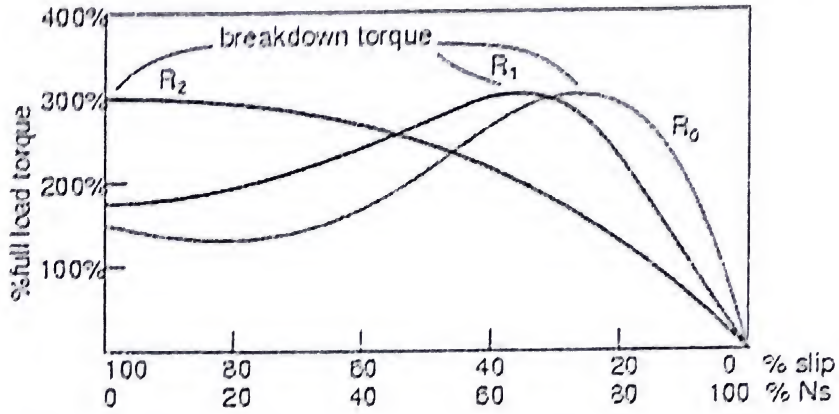


Figure (2-14) Breakdown torque peak is shifted to zero speed by increasing rotor resistance

The resistance decreases the torque available at full running speed. But that resistance is shorted out by the time the rotor is started. A shorted rotor operates like a squirrel cage rotor. Heat generated during starting is mostly dissipated external to the motor in the starting resistance. The complication and maintenance associated with brushes and slip rings is a disadvantage of the wound rotor as compared to the simple squirrel cage rotor.

This motor is suited for starting high inertial loads. A high starting resistance makes the high pull out torque available at zero speed. For comparison, a squirrel cage rotor only exhibits pull out (peak) torque at 80% of its' synchronous speed.

Speed control

Motor speed may be varied by putting variable resistance back into the rotor circuit. This reduces rotor current and speed. The high starting torque available at zero speed, the down shifted break down torque, is not available at high speed. See R_2 curve at 90% Ns, Figure below. Resistors $R_0R_1R_2R_3$ increase in value from zero. A higher resistance at R_3 reduces the speed further. Speed regulation is poor with respect to changing torque loads. This speed control technique is only useful over a range of 50% to 100% of full speed. Speed control works well with variable speed loads like elevators and printing presses.

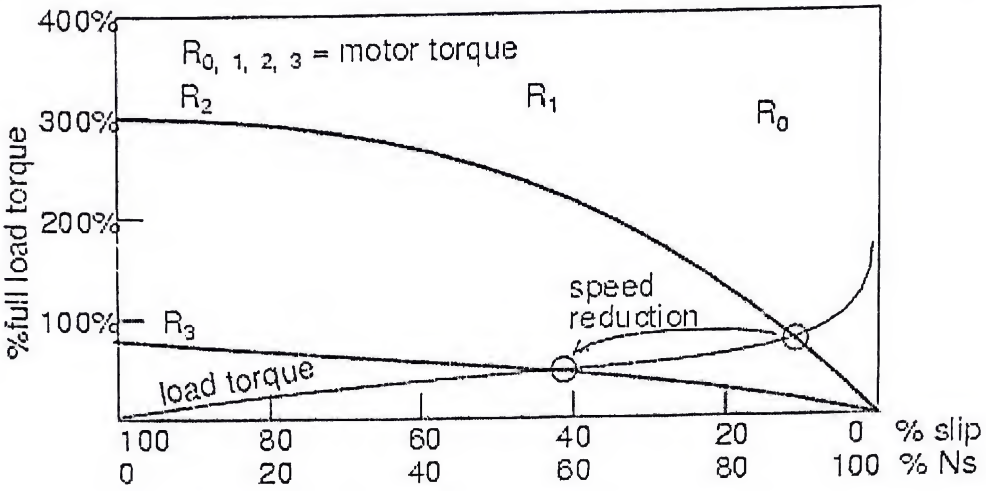


Figure (2-15) Rotor resistance controls speed of wound rotor induction motor

The available methods for speed control through rotor winding are:

- Rotor resistance control.
- Slip power recovery control.

2-1-2-1 Rotor resistance control

The speed of wound rotor IM can be changed by adding external resistance in rotor circuit .However, an increase in the rotor resistance causes:

- An increase in the rotor copper losses.

- An increase in the operating temperature of the motor.

- A reduction in the motor efficiency

Because of this drawback this method can be used only for short periods. Speed - torque characteristics are shown in figure (2-16) .It may be observed from the figure that the maximum torque is independent on the rotor resistance but both the maximum torque and the slip at which maximum torque occur increase by increasing rotor resistance.

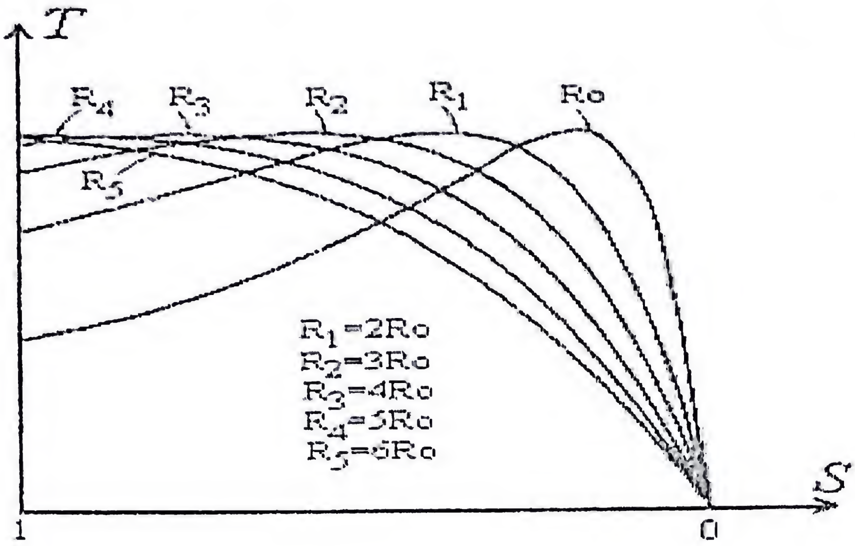


Fig (2-16) Rotor resistance control

A number of methods can be used for obtaining a variable resistance one of this methods is static rotor resistance control .In this method Instead of mechanically varying the resistance, the equivalent resistance in the rotor circuit can be varied statically by using a diode bridge rectifier and chopper as shown in figure (2-17).

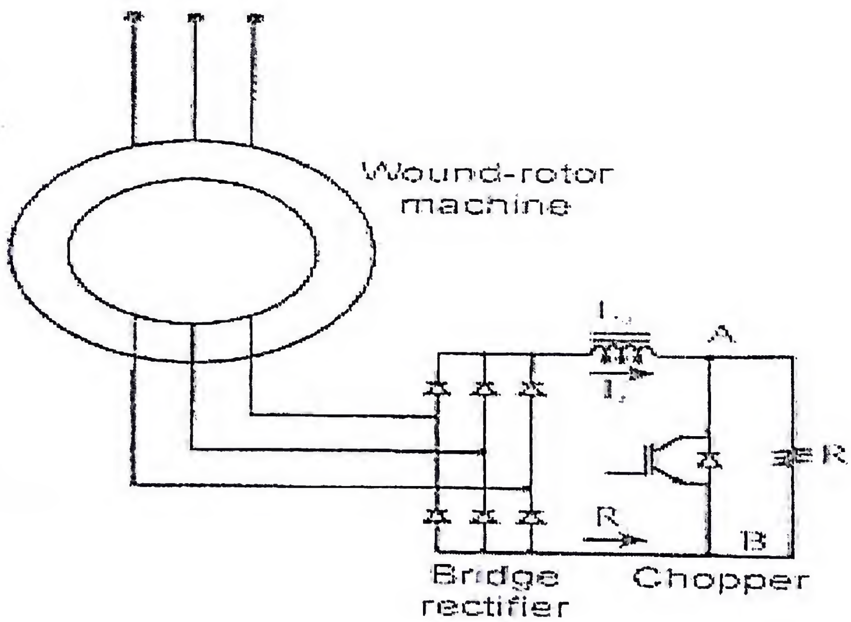


Fig **(2-17) Motor speed control with rotor circuit chopper**

As usual, the stator of the machine is connected directly to the line power supply, but in the rotor circuit, the slip voltage is rectified to dc by the diode rectifier and fed to parallel combination of fixed resistance R and a semiconductor switch realized as a transistor. Effective value of resistance across terminal A and B (R_{AB}) is varied by varying duty ratio of transistor K, which in turn varies rotor circuit resistance. Inductance L_d is added to reduce ripple and discontinuity in the dc link current I_d .

Resistance between terminal A and B will be zero when transistor is on and it will be R when it is off . Therefore, average value of resistance between the terminals will be :

$$R_{AB} = (1-K)R$$

Where K is the duty ratio of the transistor and is given by

$$K = \frac{t_{on}}{T}$$

Power consumed is given by

$$P_{AB} = I_d^2 R_{AB} = I_d^2 (1-K)R$$

Power consumed per phase is

$$P_{AB}/ph = \frac{P_{AB}}{3} = I_d^2 R_{AB} = 0.5\ I_d^2 (1-K)R$$

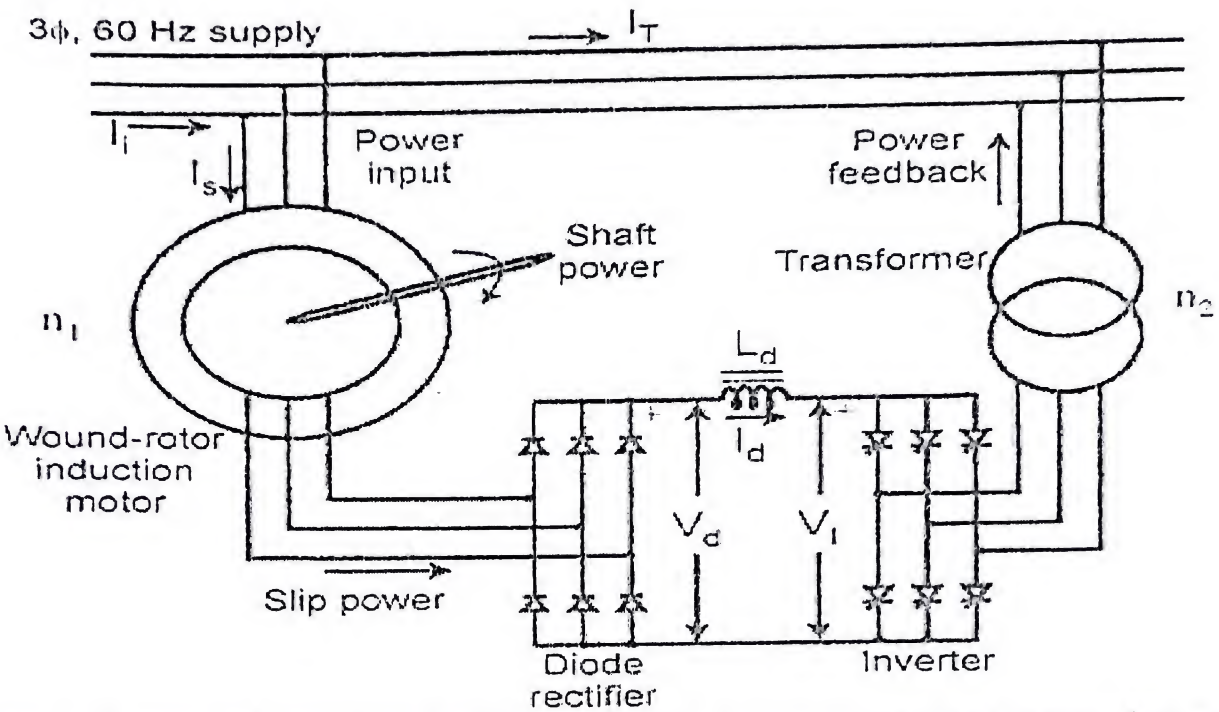
Equation (1-38) suggest that rotor circuit resistance per phase is increased by 0.5(1-k) R .Thus, total rotor circuit resistance per phase will now be

$$R_{2r} = R_2 + 0.5\ (1-K)R$$

R_{2t} can be varied from R_2 to $R_2+0.5R$ as K is changed from 1 to zero .This method has an advantage of ensuring that rotor resistance remains balanced between the phases for all operating points .

2-1-2-2 Slip power recovery method

Instead of wasting the slip power in the rotor circuit resistance, it can be converted



to ac and pumped back to the line. The slip power-controlled drive that permits only a sub synchronous range of speed control through a converter cascade is known as a static scherbius drive and the scheme is shown in Figure (2-18).

Fig (2-18) Static scherbius drive system

The static scherbius drive has been very popular in large power pump and fan-type drives, where the range of speed control is limited near, but below the synchronous speed. The drive system is very efficient and the converter power rating is low, as mentioned before, because it has to handle only the slip power. In fact, the power rating becomes lower with a more restricted range of speed control. The additional advantages, which will be explained later, are that the drive system has dc machine-like characteristics and the control is very simple. These advantages largely offset the disadvantages of the wound-rotor induction machine.

The machine air gap flux is established by the stator supply, and it practically remains constant if stator drops and supply voltage fluctuation are neglected the machine rotor current is a six-stepped wave in phase with the rotor phase voltage if the dc link current I_d is considered harmonic-free, and the commutation overlap angle of the diode rectifier is neglected .

Since the slip power is fed back to the source, unlike rotor resistance control where it is wasted in resistance, drive has a high efficiency .Drive input power is the difference between motor input power and the power fed back. Reactive power is the sum of inverter and motor reactive power; therefore, drive has a poor power.